

# Correlations of Heavy Quarks Produced at Large Hadron Collider

Mohammed Younus<sup>†‡</sup>, Umme Jamil<sup>‡</sup> §, Dinesh K. Srivastava<sup>†||</sup>

<sup>†</sup>Variable Energy Cyclotron Center, 1/AF, Bidhan Nagar, Kolkata 700 064, India

<sup>‡</sup>Saha Institute of Nuclear Physics, 1/AF, Bidhan Nagar, Kolkata 700 064, India

**Abstract.** We study the correlations of heavy quarks produced in relativistic heavy ion collisions and find them to be quite sensitive to the effects of the medium and the production mechanisms. In order to put this on a quantitative footing, as a first step, we analyze the azimuthal, transverse momentum, and rapidity correlations of heavy quark- anti quark ( $Q\bar{Q}$ ) pairs in  $pp$  collisions at  $\mathcal{O}(\alpha_s^3)$ . This sets the stage for the identification and study of medium modification of similar correlations in relativistic collision of heavy nuclei at the Large Hadron Collider. Next we study the additional production of charm quarks in heavy ion collisions due to multiple scatterings, *viz.*, jet-jet collisions, jet-thermal collisions, and thermal interactions. We find that these give rise to azimuthal correlations which are quite different from those arising from prompt initial production at leading order and at next to leading order.

*PACS:* 14.65.Dw, 25.75.-q, 25.75.Cj, 12.38.Mh, 14.40.Pq, 14.65.Fy, 12.38.-t

*Keywords:* heavy quarks, relativistic heavy ion collisions,  $pp$  collisions, quark gluon plasma, NLO pQCD, correlations, D-mesons,  $J/\psi$ .

<sup>‡</sup> E-mail: mdyounus@vecc.gov.in

<sup>§</sup> Present Address: Department of Physics, D. R. College, Golaghat, Assam 785621, India

<sup>||</sup> E-mail: dinesh@vecc.gov.in

## 1. Introduction

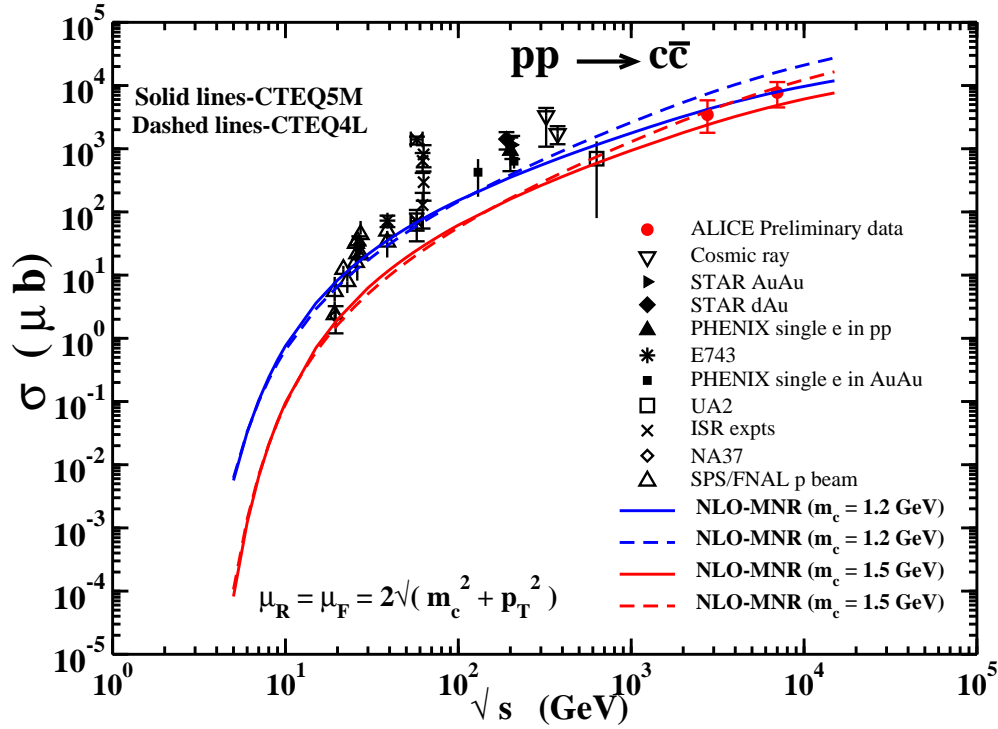
The study of relativistic heavy ion collisions and quark gluon plasma (QGP) is approaching its zenith with the first experiments performed at the Large Hadron Collider at CERN Geneva (though not yet at the top energy) involving lead nuclei. Together with the wealth of data already accumulated at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, we now have an enormous task to decipher, analyze, and quantitatively explain these observations and extract information about the properties of the QGP. These analyses are also paving the way for additional measurements, some of which can already be performed using the present detector set-ups, while others will become amenable to studies with the upgrades planned for all the major experiments, ALICE, PHENIX, and STAR, etc. Taken in its entirety, this represents the most important and fruitful international collaboration in high energy nuclear physics to date.

The focus has now progressed from models to theories and from qualitative to quantitative determination of various properties of quark gluon plasma. Enormous strides made towards exploring the shear viscosity [1] of the matter produced in these collisions is one such example.

In the present work we consider using heavy quarks to probe the QGP. The heavy quarks (only charm and bottom quarks are considered here) offer several unique advantages. The conservation of flavour in strong interaction dictates that they are produced in pairs ( $Q\bar{Q}$ ). Their large mass provides that  $Q^2$  necessary for their production is large and thus one may confidently use pQCD, for these studies. Their large masses ensure that the hadrons containing the heavy quarks stand out in the swarm of pions.

Their large mass also provides that, even though buffeted by light quarks and gluons during their passage through the quark gluon plasma, the direction of their motion may not change substantially. This should make them a valuable probe for the properties of the plasma which depend on the reaction plane. Our understanding of the effect of the dead cone [2, 3, 4] on the suppression of radiation has undergone quite some evolution since it was proposed earlier. It is also not yet clearly established that heavy quarks will completely thermalize in the plasma formed at RHIC and LHC energies (see Ref. [5]). However it must be safe to assume that the drag [6] suffered by heavy quarks will mostly slow it down and the so-called diffusion [7] processes will not alter its direction considerably. Thus, the azimuthal correlation of heavy quarks integrated over  $p_T$  may be reasonably immune to the energy loss suffered by them.

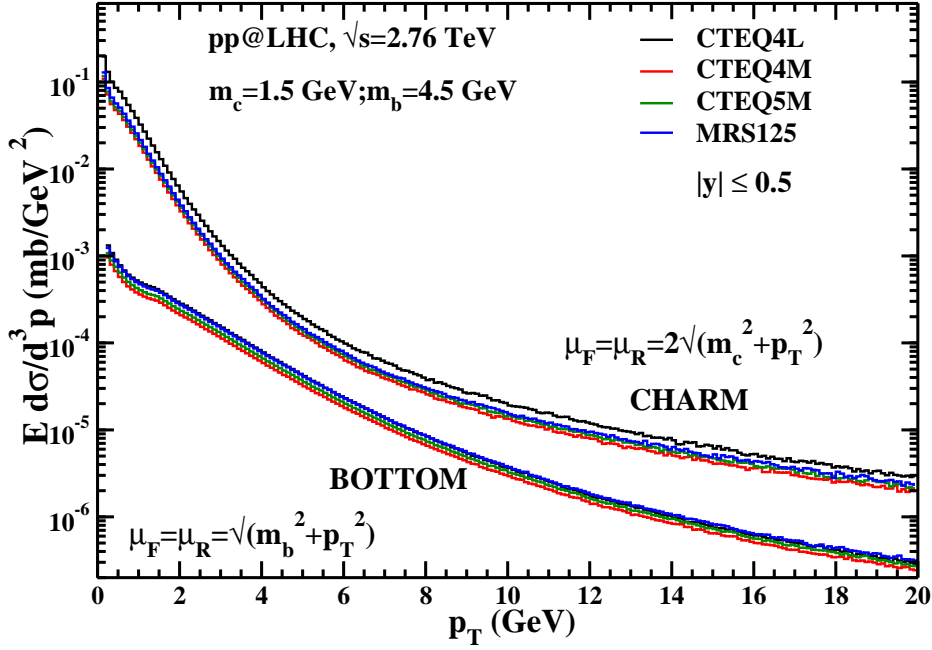
The heavy quarks could be influenced by the flow [8] generated in such collisions. If this is true, then a very interesting situation may arise for heavy quarks which is not possible for light quarks or gluons. Consider a  $Q\bar{Q}$  pair produced in a central collision having  $y = 0$ . At leading order, their transverse momenta would be equal in magnitude and point towards opposite directions. Consider a heavy quark  $Q$  moving away from the centre with momentum  $\mathbf{p}_T$ . Then its partner  $\bar{Q}$  would move with momentum  $-\mathbf{p}_T$



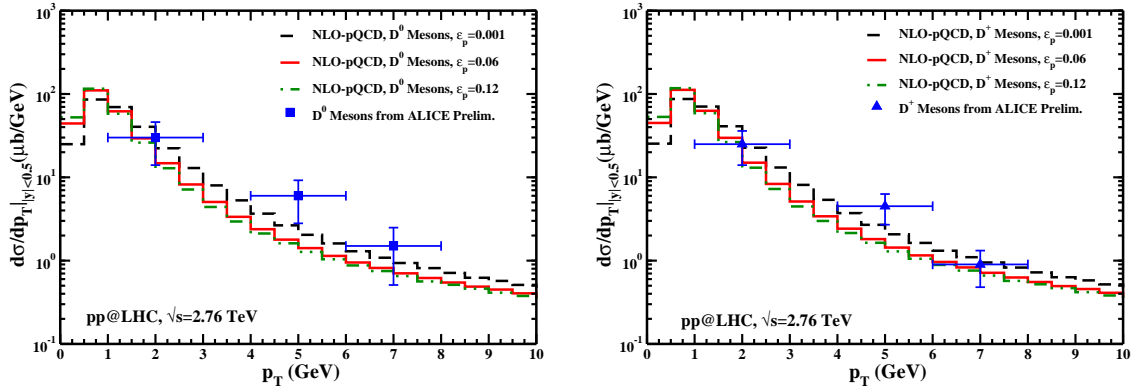
**Figure 1.** Energy dependence of the charm quark production in  $pp$  collisions.

towards the centre. Their velocities would be  $\mathbf{v}_Q = \pm \mathbf{p}_T / M_T$ , where  $M_T = \sqrt{p_T^2 + M_Q^2}$ , and  $M_Q$  is the mass of the heavy quark. Let the radial flow velocity be  $\mathbf{v}_f$ . Now if  $|\mathbf{v}_f| \geq |\mathbf{v}_Q|$ , the  $\bar{Q}$  will turn back and start moving away from the centre! Thus the  $Q\bar{Q}$  pair, which should have appeared back-to-back would appear as moving in the same direction. This would drastically alter the azimuthal correlation of the pair. A similar change of direction of motion is not possible for light quarks and gluons as they move with the speed of light. Taking, for example,  $|\mathbf{v}_f| \approx 0.6$ , (see Ref. [8]) one can see that the azimuthal correlation of charm quarks for  $p_T \leq 1.2$  GeV and for bottom quarks having  $p_T \leq 3.5$  GeV could be considerably modified from their primordial value. Recalling that non-back-to-back heavy quarks are produced from NLO processes (see later also), this would introduce an interesting richness in these studies.

Now consider charm quarks (say) produced from the primary processes  $gg \rightarrow Q\bar{Q}$  at leading order and  $gg \rightarrow gQ\bar{Q}$  at next-to-leading order. In the absence of any intrinsic  $k_T$  for partons, the quarks from the first process will be produced back-to-back, while those from the second process will be mostly collinear and will additionally be accompanied with a recoiling parton. A comparison of the energy loss suffered by the recoiling parton and the heavy-quarks will allow us to obtain flavour dependence of the energy loss. A considerable richness to this picture is added by the realization that the splitting  $g \rightarrow Q\bar{Q}$ , would produce collinear heavy quarks, while the process  $gg \rightarrow Q\bar{Q}g$ , where a gluon is radiated by one of the heavy quarks will essentially give rise to a flat azimuthal



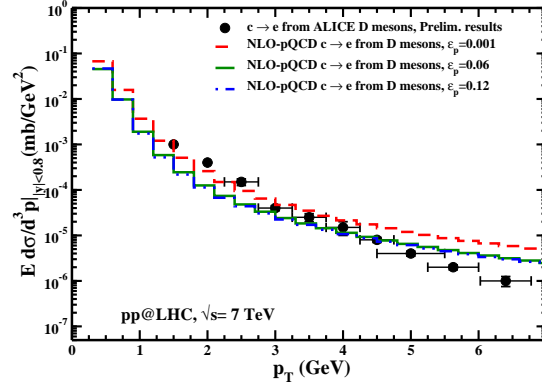
**Figure 2.** Transverse momentum distribution of the heavy quarks in the central rapidity region in  $pp$  collisions at  $\sqrt{s}=2.76$  TeV, for different structure functions using NLO pQCD.



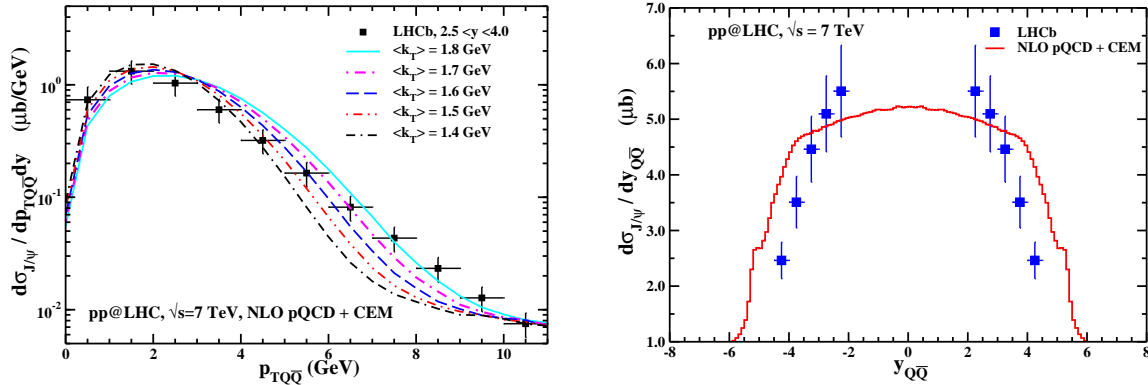
**Figure 3.** (left) Transverse momentum distribution of  $D^0$ -mesons and (right) of  $D^+$ -mesons, in  $pp$  collisions for  $\sqrt{s}=2.76$  TeV.

correlation.

So far we have discussed only the azimuthal correlation of the heavy quarks. A study of the transverse momentum of the pair and the rapidity-difference of the pair can help us disentangle the LO and the NLO processes. Recall that the transverse momentum of the  $Q\bar{Q}$  pair would be identically zero at LO and equal to that of the recoiling parton at



**Figure 4.** Transverse momentum distribution of single electrons from  $pp$  collisions at  $\sqrt{s} = 7$  TeV.

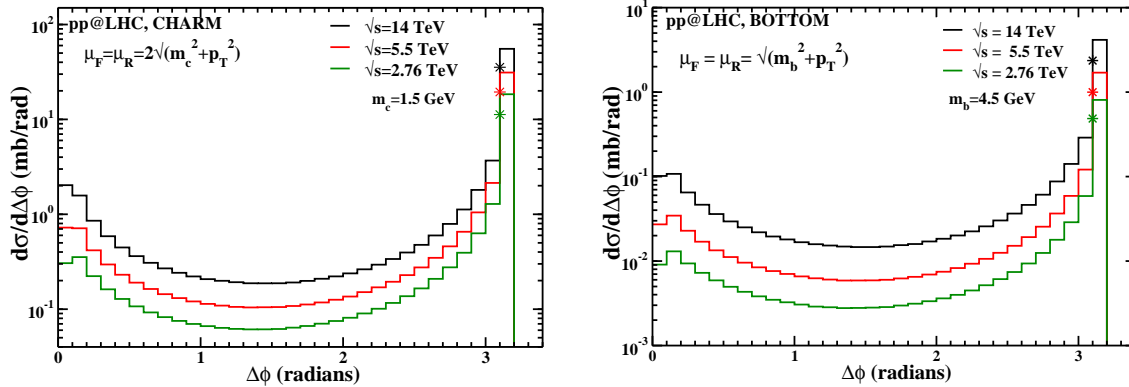


**Figure 5.** Transverse momentum (left panel) and rapidity distribution (right panel) of  $J/\psi$  from  $pp$  collision at  $\sqrt{s} = 7$  TeV, using color evaporation model.

NLO. Deviations from the results for  $pp$  collisions at the corresponding centre of mass energy in nuclear collisions will provide a measure of medium modifications as usual.

The entire discussion so far assumes that there may be no additional production of heavy quarks after the initial prompt production. Often this production for  $pp$  collisions is taken as a baseline for the study of nuclear modification factor  $R_{AA}$ . It is obvious that any additional production of heavy quarks, for example due to multiple scattering of high momentum quarks and gluons produced similarly, see Refs. [9, 10, 11, 12] or due to passage of a high energy quarks or gluons through the QGP [10, 12], or due to scattering among the thermalized partons, if the temperature is sufficiently large [10, 11, 13], will necessitate revision of our estimates for the energy loss suffered by heavy quarks as they traverse the QGP, obtained by analyzing the nuclear modification function  $R_{AA}$ , (see Ref. [14]).

By now there is also a growing realization that  $R_{AA}$  is not able to seriously



**Figure 6.** Azimuthal correlation of charm (left panel) and bottom (right panel) quarks at 2.76, 5.5 and 7 TeV for  $pp$  collisions. The symbols give the LO values for  $d\sigma/d\phi = \sigma_{\text{LO}}/\delta(\Delta\phi)$  where  $\delta(\Delta\phi)$  is the size of  $\phi$  bin.

discriminate between different mechanisms of energy loss and evolution of the system [15] and the correlation of the leading hadrons are slowly emerging as more discerning probes [16]. Consider a simple example. We need to know the transverse momentum of heavy quarks in  $pp$  collisions in order to have a base-line to estimate the nuclear modifications. The NLO pQCD results for these are easily approximated by a  $K$  factor multiplying the results for LO pQCD (see eg. Ref. [17]). Now consider the azimuthal correlations of heavy quarks produced in similar collisions. As we discussed above, the LO pQCD results for the correlation is a delta function around  $\Delta\phi = \pi$ . However, we shall see that the correlation function estimated at NLO, though still peaking at  $\Delta\phi = \pi$  fills up the phase-space from zero to  $\pi$  with an interesting catenary like structure. Considering that one uses deviations from  $pp$  collisions to obtain results for nuclear modifications, these will have to be quantitatively understood for  $pp$  collisions before we can accurately decipher the later.

The present work aims at investigating azimuthal, momentum, and rapidity correlations for heavy quark-anti quark pairs for  $pp$  collisions and setting the stage for the study of the deviations in these due to medium modifications in heavy ion collisions at the corresponding energies. We also discuss the complexities arising from the additional production of heavy quarks due to multiple scatterings.

The paper is organized as follows. In the next section we discuss various correlations for  $pp$  collisions using NLO pQCD. In Sect. 3 we discuss the azimuthal correlations in Pb+Pb collisions due to initial production and various multiple collisions. Our results for  $pp$  and Pb+Pb collisions are discussed in Sect. 4 followed by conclusion in Sect. 5.

## 2. Proton Proton Collisions

The results for particle and photon productions in  $pp$  collisions serve as a baseline in search for quark-gluon-plasma and other medium effects at the corresponding centre of mass energy/nucleon for collision of heavy nuclei. This paradigm may have to be modified if the recent suggestions for formation of QGP (perhaps only in high multiplicity events), Ref. [18] in  $pp$  collisions turn out to be valid. An alternative criterion of comparing results for peripheral collisions to those for central collisions has also been used with considerable success, with the understanding that the peripheral collisions may be considered as a superposition of  $pp$  collisions.

The correlation of heavy quarks produced in  $pp$  collisions is defined in general as:

$$E_1 E_2 \frac{d\sigma}{d^3p_1 d^3p_2} = \frac{d\sigma}{dy_1 dy_2 d^2p_{T1} d^2p_{T2}} = C, \quad (1)$$

where  $y_1$  and  $y_2$  are the rapidities of heavy quark and anti-quark and  $\mathbf{p}_{T\mathbf{i}}$  are their transverse momenta.

At the leading order, the differential cross-section for the charm correlation from proton-proton collision can be written as:

$$C_{LO} = \frac{d\sigma}{d^2p_T dy_1 dy_2} \delta(\mathbf{p}_{T1} + \mathbf{p}_{T2}). \quad (2)$$

In the above  $\mathbf{p}_{T1} = \mathbf{p}_{T2} = \mathbf{p}_T$  and

$$\begin{aligned} \frac{d\sigma}{dy_1 dy_2 dp_T} = 2x_a x_b p_T \sum_{ij} \left[ f_i^{(a)}(x_a, Q^2) f_j^{(b)}(x_b, Q^2) \frac{d\hat{\sigma}_{ij}(\hat{s}, \hat{t}, \hat{u})}{d\hat{t}} \right. \\ \left. + f_j^{(a)}(x_a, Q^2) f_i^{(b)}(x_b, Q^2) \frac{d\hat{\sigma}_{ij}(\hat{s}, \hat{u}, \hat{t})}{d\hat{t}} \right] / (1 + \delta_{ij}), \end{aligned} \quad (3)$$

where  $x_a$  and  $x_b$  are the fractions of the momenta carried by the partons from their interacting parent hadrons. These are given by

$$x_a = \frac{M_T}{\sqrt{s}} (e^{y_1} + e^{y_2}); \quad x_b = \frac{M_T}{\sqrt{s}} (e^{-y_1} + e^{-y_2}). \quad (4)$$

where  $M_T$  is the transverse mass,  $\sqrt{m_Q^2 + p_T^2}$ , of the produced heavy quark. The subscripts  $i$  and  $j$  denote the interacting partons, and  $f_i$  and  $f_j$  are the partonic distribution functions for the nucleons. We shall use CTEQ5M structure function, though we have checked that similar results are obtained for other modern structure functions (see later). The differential cross-section for partonic interactions,  $d\hat{\sigma}_{ij}/d\hat{t}$  is given by

$$\frac{d\hat{\sigma}_{ij}}{d\hat{t}} = \frac{|M|^2}{16\pi\hat{s}^2}, \quad (5)$$

where  $|M|^2$  is the invariant amplitude for different sub-processes as obtained from Ref. [19]. The physical sub-processes included for the leading order,  $\mathcal{O}(\alpha_s^2)$  production of heavy quarks are:

$$\begin{aligned} g + g &\rightarrow Q + \bar{Q} \\ q + \bar{q} &\rightarrow Q + \bar{Q}. \end{aligned} \quad (6)$$

At next-to-leading order,  $\mathcal{O}(\alpha_s^3)$  subprocesses included are as follows

$$\begin{aligned} g + g &\rightarrow Q + \bar{Q} + g \\ q + \bar{q} &\rightarrow Q + \bar{Q} + g \\ g + q(\bar{q}) &\rightarrow Q + \bar{Q} + q(\bar{q}) . \end{aligned} \tag{7}$$

We show our results for azimuthal correlation  $C(\Delta\phi)$ , where  $\Delta\phi=|\phi_1 - \phi_2|$  as well as rapidity correlations,  $C(\Delta y)$ , where  $\Delta y=y_1 - y_2$ , of produced heavy quarks. We also present  $(\Delta\eta, \Delta\phi)$  correlations in the jet radius parameter,  $R$ , where  $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$  along with the transverse momentum, invariant mass, and rapidity of the pair.

We verify the accuracy of our results by evaluating the production of  $J/\psi$  and charm measured recently.

### 3. Lead Lead Collisions

Let us now move towards Pb+Pb collisions under study at the Large Hadron Collider (LHC). We have discussed that most of the heavy-quarks and so also quarks and gluons having large transverse momenta are produced in initial hard collisions. At the energies reached at the LHC, the sheer number of quarks and gluons produced in these collisions leads to vehement multiple collisions and gluon multiplication. This then leads to a quark-gluon plasma at a very large initial temperature.

As discussed earlier, we would like to know if these initial temperatures are large enough to produce heavy quarks as well (see eg. Ref. [13]). The multiple collisions among the very high momentum quarks and gluons (the so called jet-jet collisions) have been seen earlier to produce substantial number of heavy quarks. These jets, produced at very early times  $\tau \approx 1/p_T$  will have to necessarily pass through the QGP which will be formed only after  $\tau \approx 0.1 \text{ fm}/c$ . Do these lead to a substantial production of heavy quarks? Some of these questions have been addressed earlier [9, 10, 11, 12].

Since those early studies, several new developments have taken place. We now know the particle rapidly density (see eg. Ref. [20]), important to calculate the initial conditions, for which only values estimated by several authors were known earlier. There has, now, been a growing realization that jet-quenching measured in terms of the nuclear modification function  $R_{AA}$  is not able to seriously discriminate between various theories of evolution of the plasma and the mechanism of energy loss. Thus correlations are being studied more closely to help us in this enterprise.

Thus we extend our earlier study [10] to explore the correlations of heavy quarks in collision of heavy nuclei due to initial production and various multiple collisions, e.g., jet-jet interactions, jet-plasma interactions, and the scattering of thermal partons, to see if these processes make large contribution to the correlation. This is important as, at least the jet-jet collision was found to make a large contribution to the production of heavy quarks [10].



### 3.1. Prompt Interactions

The basic formulation which gives the correlation of produced heavy quarks from initial fusion of gluons and quark-anti quark annihilation in proton-proton collision is given by Eq. 1. Thus the azimuthal distribution of heavy quark for Pb+Pb collision at  $b = 0$  is given by

$$E_1 E_2 \frac{dN}{d^3 p_1 d^3 p_2} = T_{AA} E_1 E_2 \frac{d\sigma_{pp}}{d^3 p_1 d^3 p_2} . \quad (8)$$

For central collisions of lead nuclei, the nuclear thickness function is taken as  $T_{AA} = 292 \text{ fm}^{-2}$ . In the above  $\mathbf{p}_1$  and  $\mathbf{p}_2$  are the momenta of the heavy quarks produced.

### 3.2. Jet-Jet Interaction

The initial hard scattering will produce massless gluons and light quarks in large numbers. These partons have large transverse momenta. These quarks and gluons may ultimately thermalize because of frequent interactions among themselves and if sufficient energy is available, their interactions may lead to the production of heavy quarks as well. Here we give the formulation for azimuthal distribution of produced heavy quarks pair from jet-jet interaction. Since the jet-jet contribution to the heavy quark production is comparable to that of primary production [9, 10], it should be interesting to see if their azimuthal distributions differ.

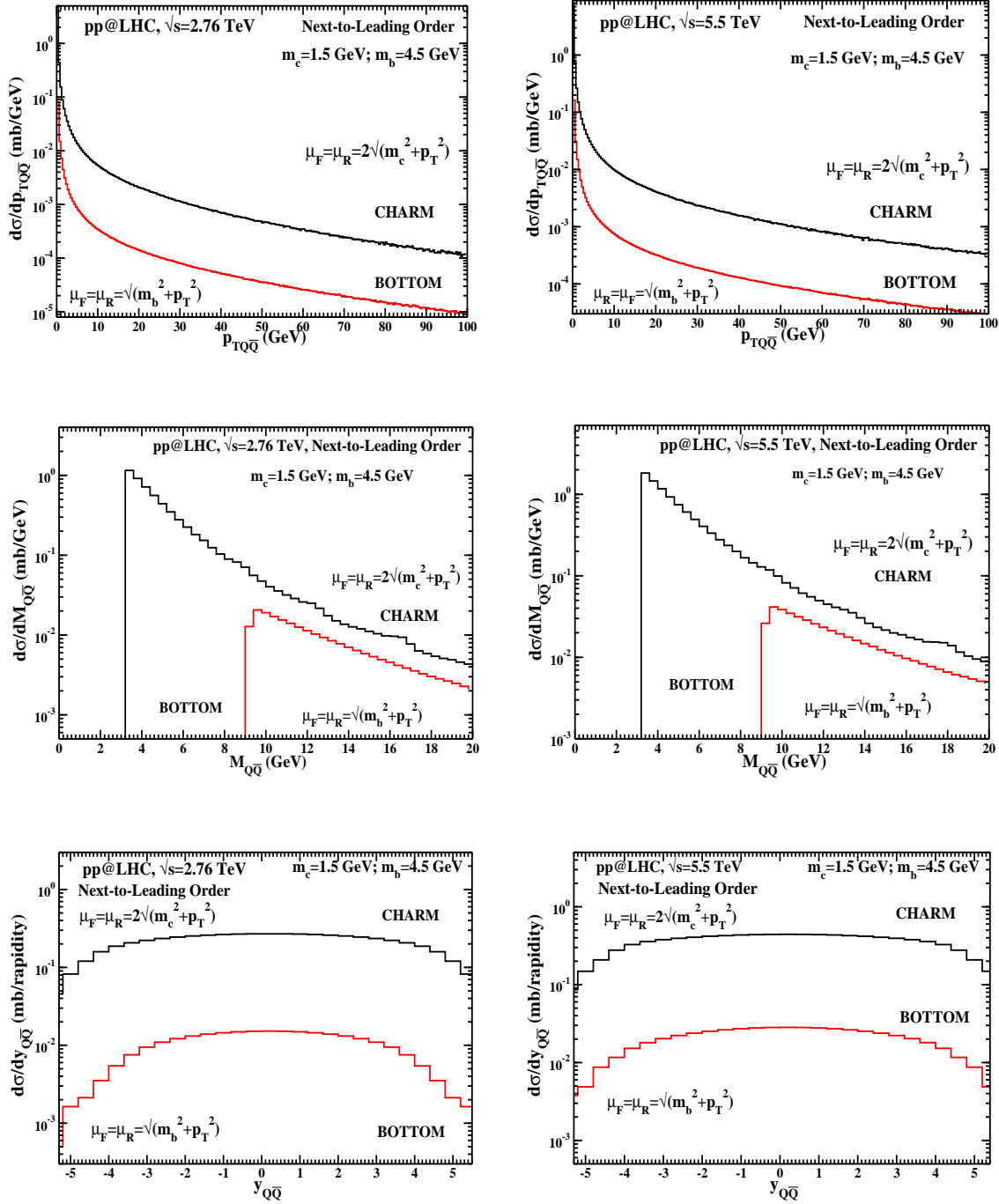
As a first step we obtain the distribution of light partons, having  $p_T > 2 \text{ GeV}$ , from a LO pQCD calculation using CTEQ5M structure function, for  $pp$  collisions at 2.76 TeV and 5.5 TeV. We parametrize them as:

$$\begin{aligned} \frac{dN}{dy d^2 p_T} &= T_{AA} \frac{d\sigma_{pp}^{\text{jet}}}{d^2 p_T dy} \Big|_{y=0} \\ &= K \frac{C}{(1 + p_T/B)^\beta} \\ &= h_{\text{jet}}(p_T) , \end{aligned} \quad (9)$$

where the  $K$  factor is taken as 2.5 to account for higher order effects and the parameters  $C$ ,  $B$ , and  $\beta$  are given in Table 1. The factorization and renormalization scales are chosen as  $Q = p_T$

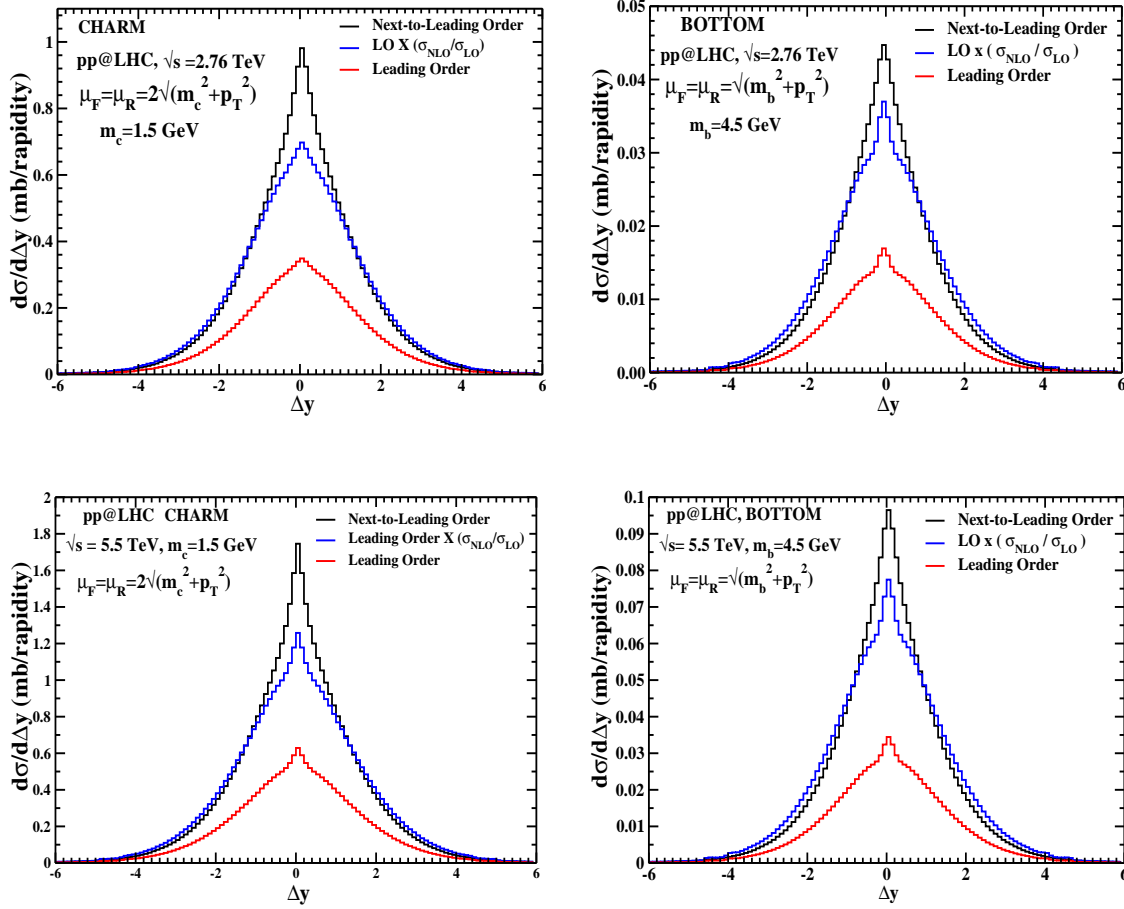
Now the azimuthal distribution of heavy quarks for collisions having an impact parameter,  $b = 0$ , due to jet-jet interaction can be written as:

$$\begin{aligned} E_1 E_2 \frac{dN}{d^3 p_1 d^3 p_2} &= \frac{1}{16(2\pi)^8} \int d^4 x \int \frac{d^3 p_a d^3 p_b}{\omega_a \omega_b} \delta^4(\Sigma p^\mu) \\ &\times \left[ \frac{1}{2} g_g^2 f_{\text{jet}}^g(p_{Ta}) f_{\text{jet}}^g(p_{Tb}) \left| M_{gg \rightarrow Q\bar{Q}} \right|^2 \right. \\ &\left. + g_q^2 \sum_i \left\{ f_{\text{jet}}^{q_i}(p_{Ta}) f_{\text{jet}}^{\bar{q}_i}(p_{Tb}) \left| M_{q\bar{q} \rightarrow Q\bar{Q}} \right|^2 + (q_i \leftrightarrow \bar{q}_i) \right\} \right] , \end{aligned} \quad (10)$$



**Figure 7.** Transverse momentum, invariant mass and rapidity distribution of charm and bottom quark pairs at LHC.

where  $p_a, p_b$  are the four momenta of the incoming partons and  $p_1$  and  $p_2$  are the same for the outgoing heavy quarks, and  $q_i$  stands for the flavour of the light quarks. The jet



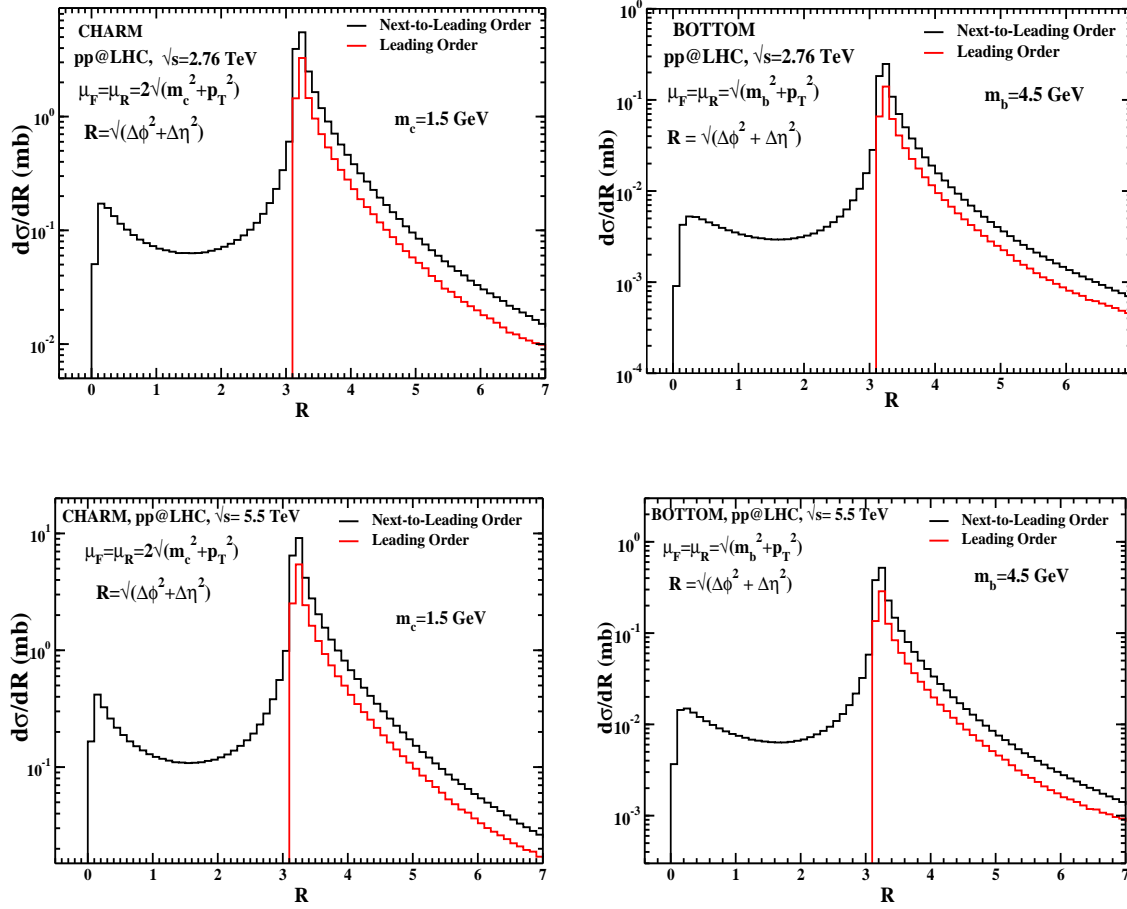
**Figure 8.** Rapidity difference of  $\Delta y = y_Q - y_{\bar{Q}}$ , of charm and bottom quarks at LO and NLO in pp collisions.

distribution function  $f_{\text{jet}}(p_T)$  is given by

$$f_{\text{jet}}^i(p_T) = \frac{(2\pi)^3}{g_i \tau \pi R_T^2 p_T} \frac{dN_i}{d^2 p_T dy} \delta(y - \eta) \Theta(\tau_f - \tau) \Theta(\tau - \tau_i). \quad (11)$$

This follows the Bjorken space-time correlation used earlier in Refs. [9, 10, 21]. In the above,  $p_T$  is the transverse momentum,  $y$  is rapidity,  $\eta$  is the space-time rapidity, and  $g_i$  is the spin-colour degeneracy of the partons, which is  $2 \times 8$  for gluons and  $2 \times 3$  for quarks. As indicated earlier,  $\tau_i$  and  $\tau_f$  are the the formation time of the jet and the life time of the plasma.  $R_T$  is the transverse size of the system. Now the Eq. 10 reduces to:

$$\begin{aligned} E_1 E_2 \frac{dN}{d^3 p_1 d^3 p_2} &= \frac{1}{16(2\pi)^8} \int d^4 x \int d^2 p_{Tb} dy_b \frac{\delta(\Sigma E)}{\omega_a} \\ &\times \left[ \frac{1}{2} g_g^2 f_{\text{jet}}^g(p_{Ta}) f_{\text{jet}}^g(p_{Tb}) \left| M_{gg \rightarrow Q\bar{Q}} \right|^2 + g_q^2 \times \right. \\ &\left. \sum_i \left\{ f_{\text{jet}}^{q_i}(p_{Ta}) f_{\text{jet}}^{\bar{q}_i}(p_{Tb}) \left| M_{q\bar{q} \rightarrow Q\bar{Q}} \right|^2 + (q_i \leftrightarrow \bar{q}_i) \right\} \right], \quad (12) \end{aligned}$$



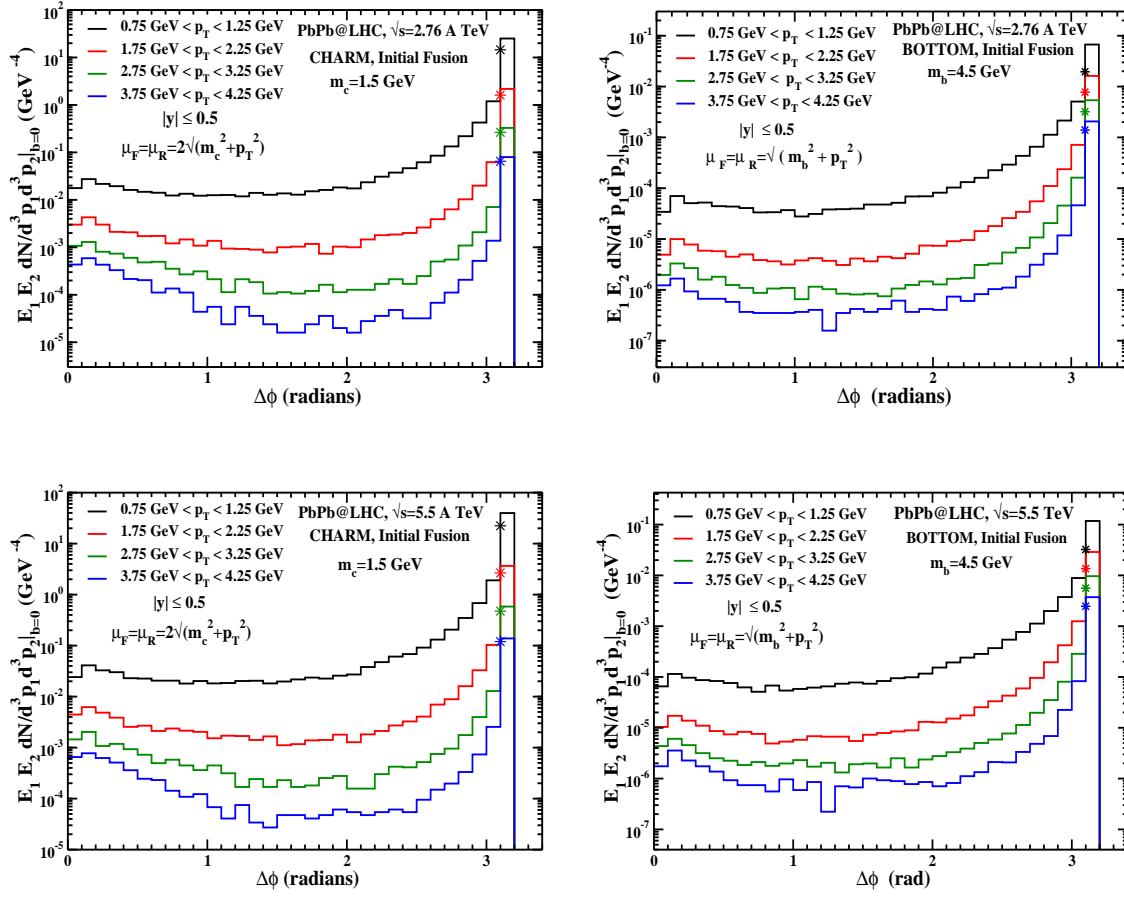
**Figure 9.**  $(\Delta\eta, \Delta\phi)$  correlations of heavy quarks produced in  $pp$  collisions at  $\sqrt{s}=2.76$  TeV and 5.5 TeV at LO and NLO.

where  $d^4x = \tau d\tau r dr d\eta d\phi_r$  and  $d^3p = p_T dp_T d\phi_p E dy$ . Further

$$\frac{\delta(\Sigma E)}{\omega_a} = \frac{\delta(p_{Tb} - p_{Tb0})}{[p_{T1} \cos(\phi_1 - \phi_b) + p_{T2} \cos(\phi_2 - \phi_b) - M_{T1} \cosh(y_1 - \eta) - M_{T2} \cosh(y_2 - \eta)]} \cdot \quad (13)$$

Thus the final integration obtained by putting the above expression in Eq. 12 reduces to:

$$\begin{aligned} E_1 E_2 \frac{dN}{d^3p_1 d^3p_2} &= \frac{\ln(\tau_f/\tau_i)}{16(2\pi)^2 \pi R_T^2} \int d\eta d\phi_b \\ &\times \frac{1}{p_{Ta} [p_{T1} \cos(\phi_1 - \phi_b) + p_{T2} \cos(\phi_2 - \phi_b) - M_{T1} \cosh(y_1 - \eta) - M_{T2} \cosh(y_2 - \eta)]} \\ &\times \left[ \frac{1}{2} h_{\text{jet}}^g(p_{Ta}) h_{\text{jet}}^g(p_{Tb0}) \left| M_{gg \rightarrow Q\bar{Q}} \right|^2 \right] \end{aligned}$$



**Figure 10.** (Colour on-line) Azimuthal correlation of heavy quarks from prompt interaction for lead on lead collisions at LHC, having different transverse momenta and rapidities close to zero. The symbols give the corresponding LO values, with the same bin-size for  $\Delta\phi$ . The upper panels are for 2.76 ATeV while the lower panels give results for 5.5 ATeV. The left panels give results for charm quarks while the right panels give the results for bottom quarks.

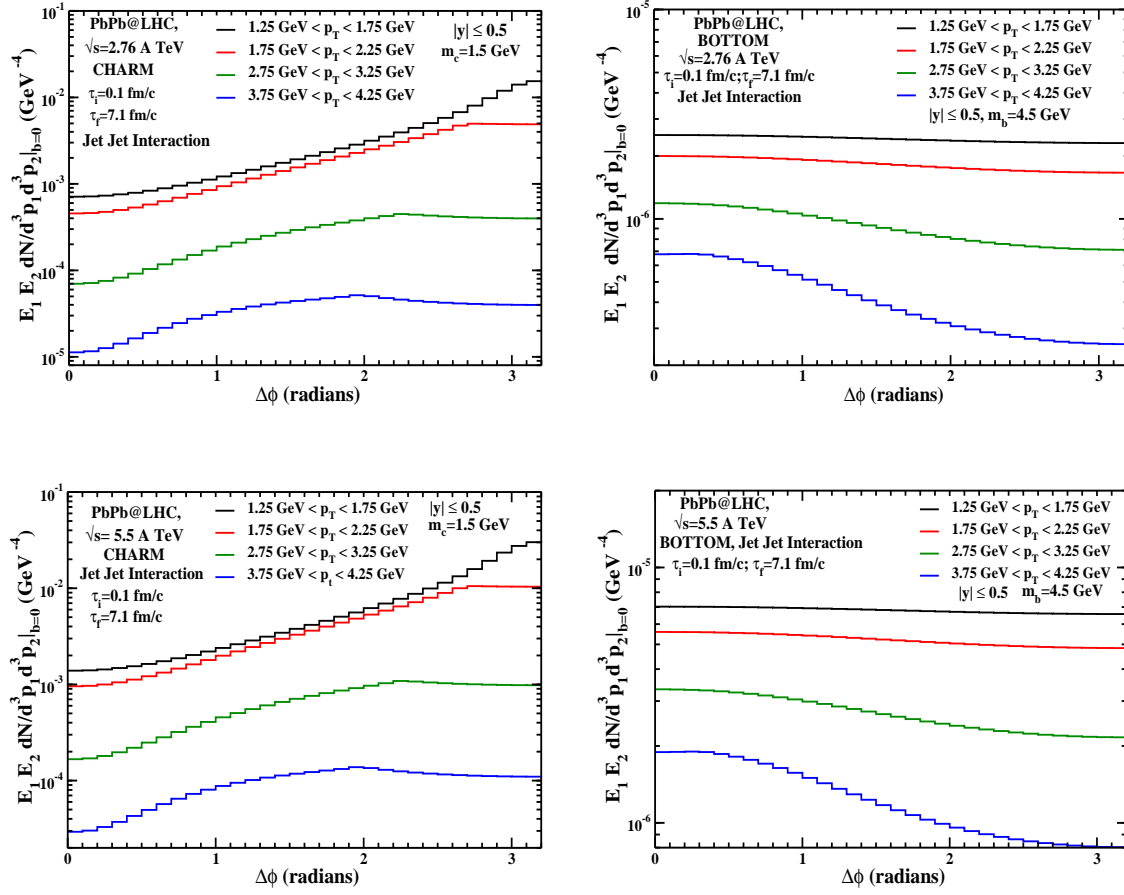
$$+ \sum_i \left\{ h_{\text{jet}}^{q_i}(p_{Ta}) h_{\text{jet}}^{\bar{q}_i}(p_{Tb0}) \left| M_{q\bar{q} \rightarrow Q\bar{Q}} \right|^2 + (q_i \leftrightarrow \bar{q}_i) \right\} . \quad (14)$$

with  $p_{Tb0}$  given by,

$$p_{Tb0} = \frac{p_{T1} p_{T2} \cos(\phi_1 - \phi_2) - M_{T1} M_{T2} \cosh(y_1 - y_2) - m_Q^2}{p_{T1} \cos(\phi_1 - \phi_b) + p_{T2} \cos(\phi_2 - \phi_b) - M_{T1} \cosh(y_1 - \eta) - M_{T2} \cosh(y_2 - \eta)} \quad (15)$$

These are similar to the expressions obtained earlier by Levai et al [11].

The formation time for the jets (light  $p_T$  partons) is taken as  $\tau_i = 0.1 \text{ fm}/c$ , as we count those having  $p_T > 2 \text{ GeV}$ , as jets. We take  $\tau_f \approx R_T$ , of the system and perform rest of the integration numerically. Note, however, that  $\tau_i$  and  $\tau_f$  appear in the above



**Figure 11.** Azimuthal correlation of heavy quarks from jet-jet interaction for lead on lead collisions at LHC, for different transverse momenta.

expression only through the term  $\ln(\tau_f/\tau_i)$  and thus reasonable variations in their values will lead to only a modest variation in the results.

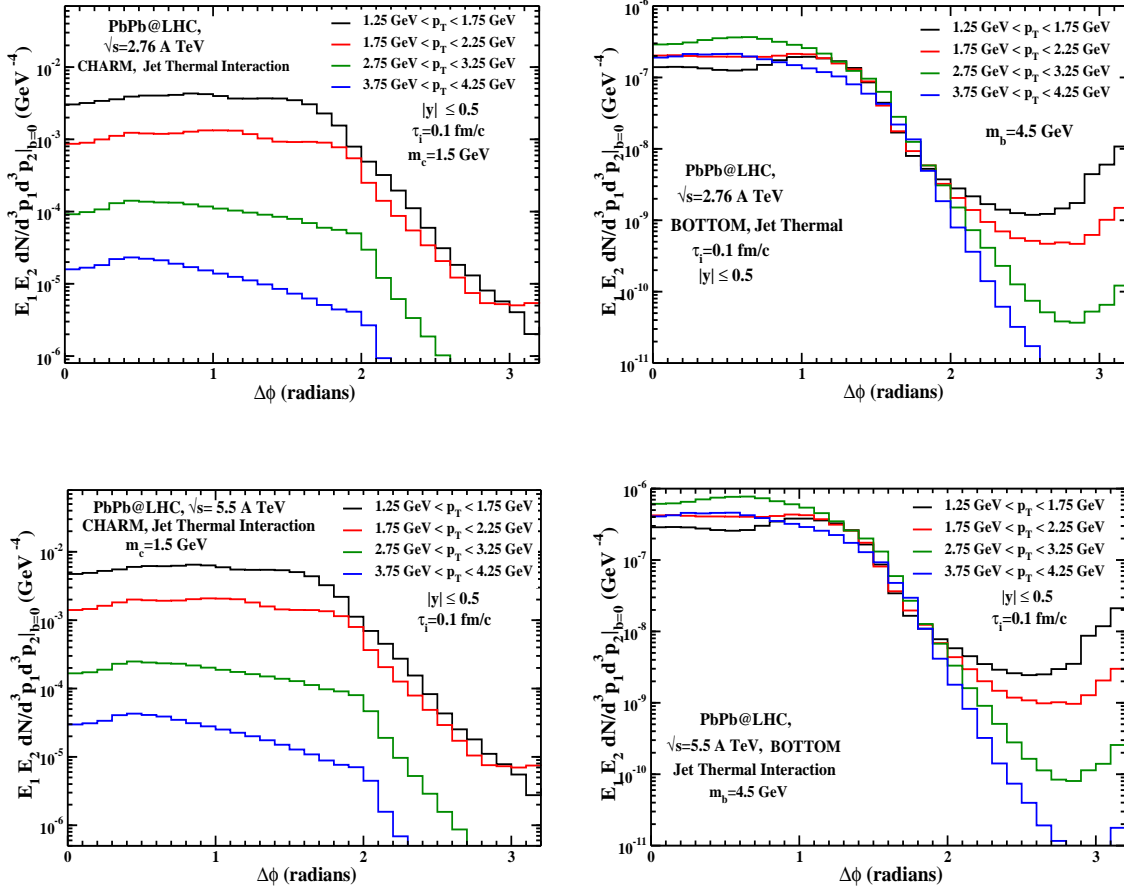
### 3.3. Jet-Thermal Interaction

Now, we consider passage of high energy energy jets through quark gluon plasma and estimate azimuthal dependence of the produced heavy quarks.

Suppose, a light parton is produced at position  $\mathbf{r}$ , and moves at an angle  $\alpha$  where  $\cos \alpha = \hat{r} \cdot \hat{d}$ , then the distance  $d$  travelled by the jet along the direction  $\hat{d}$ , before it reaches the surface is given by:

$$d = -r \cos \alpha + \sqrt{R^2 + r^2 \sin^2 \alpha}, \quad (16)$$

Hence the time available for heavy quark production is the minimum of  $[\tau_d, \tau_f]$ , where  $\tau_d$  is time taken by the parton to cover the distance  $d$  and  $\tau_f$  is the time when quark gluon plasma hadronizes.



**Figure 12.** Azimuthal correlation of heavy quarks from jet-thermal interaction for lead on lead collisions at LHC, for different transverse momenta.

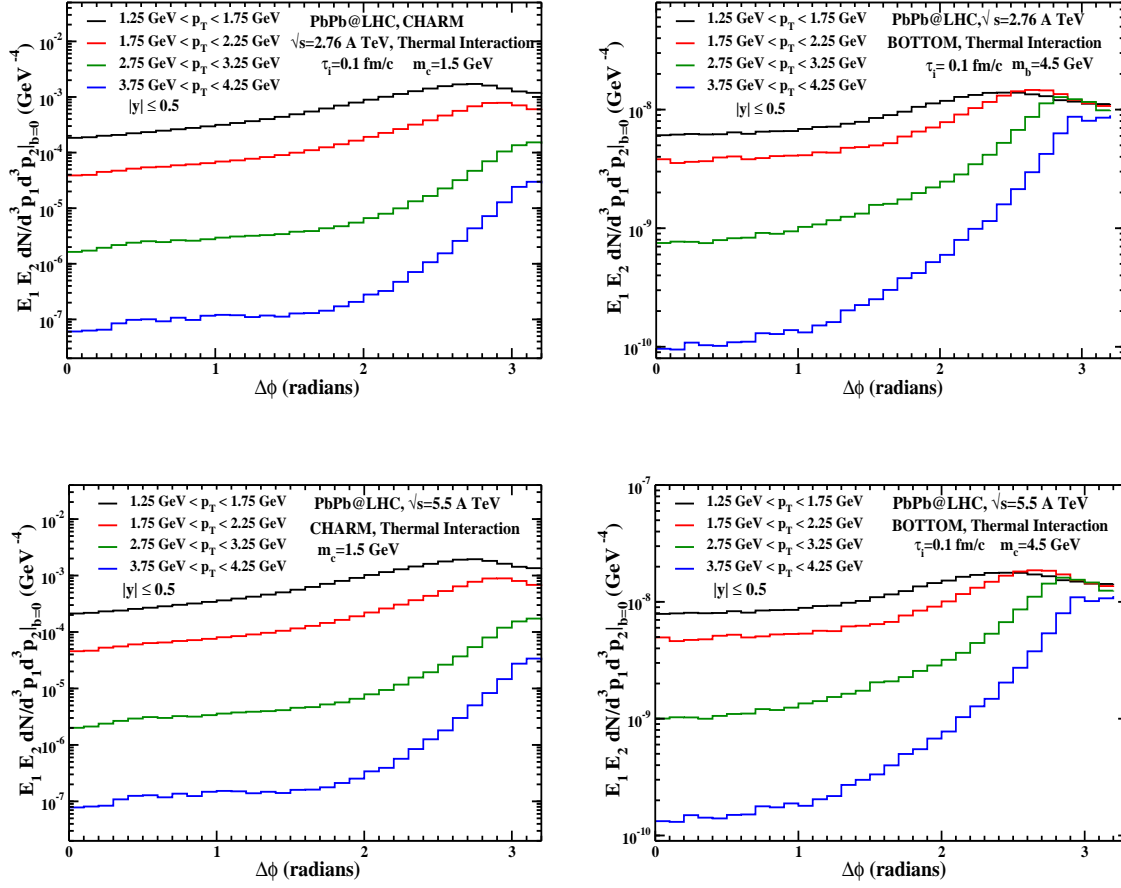
The azimuthal distribution of the produced heavy quark from jet-thermal interaction is given by

$$\begin{aligned}
 E_1 E_2 \frac{dN}{d^3p_1 d^3p_2} &= \frac{1}{16(2\pi)^8} \int d^4x \int d\phi_b dy_b \\
 &\times \frac{p_{Tb0}}{[p_{T1} \cos(\phi_1 - \phi_b) + p_{T2} \cos(\phi_2 - \phi_b) - M_{T1} \cosh(y_1 - y_b) - M_{T2} \cosh(y_2 - y_b)]} \\
 &\times \left[ \frac{1}{2} g_g^2 f_{\text{jet}}^g(p_{Ta}) f_{\text{th}}^g(p_{Tb0}) |M_{gg \rightarrow Q\bar{Q}}|^2 \right. \\
 &\left. + g_q^2 \sum_i \left\{ f_{\text{jet}}^{q_i}(p_{Ta}) f_{\text{th}}^{\bar{q}_i}(p_{Tb0}) |M_{q\bar{q} \rightarrow Q\bar{Q}}|^2 + (q_i \leftrightarrow \bar{q}_i) \right\} \right], \quad (17)
 \end{aligned}$$

The  $p_T$  distribution for jet partons is given in Eq. 9. The distribution of the thermal partons and the cooling of the plasma is given in the Sect. 3.4.

After some simplifications, the final result is given by

$$E_1 E_2 \frac{dN}{d^3p_1 d^3p_2} = \frac{1}{16(2\pi)^4 \pi R_T^2} \int r dr d\tau d\eta d\phi_b dy_b$$



**Figure 13.** Azimuthal correlation of heavy quarks from thermal interaction for lead on lead collisions at LHC, for different transverse momenta.

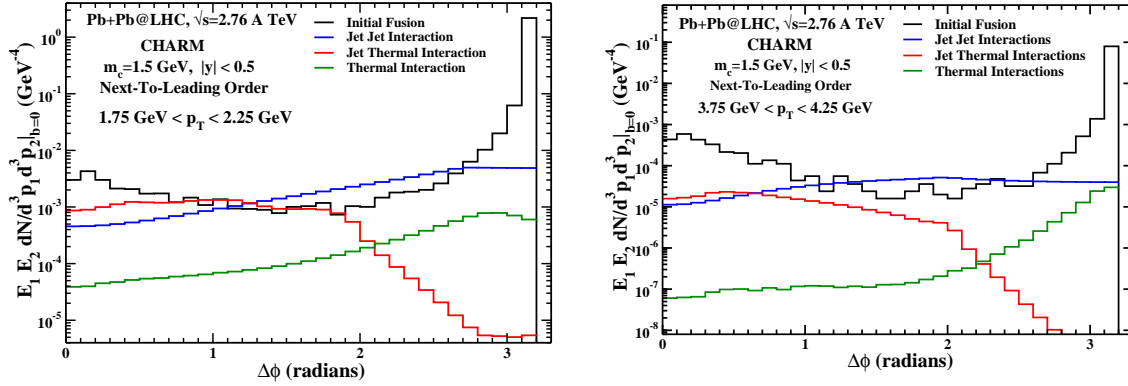
$$\begin{aligned}
 & \times \frac{p_{Tb0}}{p_{Ta}[p_{T1} \cos(\phi_1 - \phi_b) + p_{T2} \cos(\phi_2 - \phi_b) - M_{T1} \cosh(y_1 - y_b) - M_{T2} \cosh(y_2 - y_b)]} \\
 & \times \left[ \frac{1}{2} g_g h_{\text{jet}}^g(p_{Ta}) f_{\text{th}}^g(p_{Tb0}) |M_{gg \rightarrow Q\bar{Q}}|^2 \right. \\
 & \left. + g_q \sum_i \left\{ h_{\text{jet}}^{q_i}(p_{Ta}) f_{\text{th}}^{q_i}(p_{Tb0}) |M_{q\bar{q} \rightarrow Q\bar{Q}}|^2 + (q_i \leftrightarrow \bar{q}_i) \right\} \right] . \quad (18)
 \end{aligned}$$

which is then evaluated numerically.

### 3.4. Thermal Interaction

We have discussed earlier that the multiple scatterings among the quarks and gluons leads to the formation of quark gluon plasma at a large initial temperature. An interaction among the thermalized partons may also lead to charm production provided the initial temperature of quark gluon plasma is high. Using the recent results from ALICE at  $\sqrt{s}=2.76$  A TeV for central collisions of lead-lead nuclei, we take particle multiplicity density to be  $dN/dy=2850$  at  $\sqrt{s}=2.76$  TeV/nucleon, [20] and extrapolate





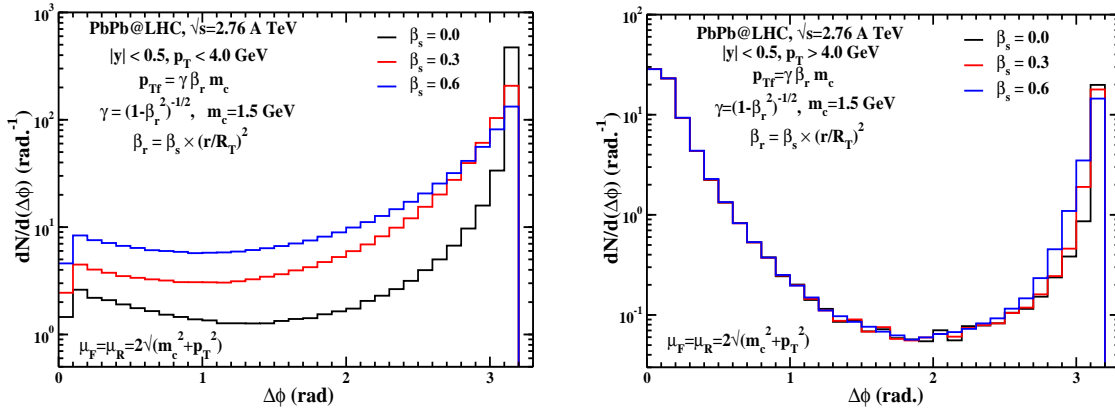
**Figure 14.** Relative contributions of prompt, jet-jet, jet-thermal, and thermal productions of charm quarks having transverse momenta of about 2 GeV/c (left panel) and 4 GeV/c (right panel) to their azimuthal correlation.

it to 3000 for  $\sqrt{s} = 5.5$  TeV/nucleon. Now using the relation [22]

$$\frac{2\pi^4}{45\zeta(3)\pi R_T^2} \frac{dN}{dy} = 4aT_0^3\tau_0 \quad (19)$$

and initial formation time for QGP,  $\tau_i=0.1$  fm/c, we estimate  $T_0$  to be 653 MeV at 2.76 TeV/nucleon and 664 MeV at 5.5 TeV/nucleon respectively.

Recall also that at RHIC energies,  $\tau_i$  up to 0.6 fm/c have been used, specially to for the part of the evolution which could be described using hydrodynamics. One may imagine  $\tau_i$  getting smaller at LHC energies, due to increased activity of minijets, etc. Thus for example, the parton saturation models [23] suggest that  $p_{\text{sat}}$  at LHC energies is close to 2 GeV, which suggests that the initial time  $\tau_i$  for the plasma would be  $\approx 1/p_{\text{sat}}$



**Figure 15.** Azimuthal correlation of heavy quarks from prompt interaction for lead on lead collisions at LHC, with flow

**Table 1.** Parametrization of the quark and gluon distributions from initial scattering of partons at 2.76 and 5.5 TeV in  $pp$  collisions, using LO pQCD and CTEQ5M structure functons, for  $p_T > 2$  GeV.

$\sqrt{s}$ [TeV]		C [ $1/\text{GeV}^2$ ]	B [GeV]	$\beta$
2.76	u	$1.078 \times 10^3$	1.127	5.615
	d	$1.279 \times 10^3$	1.099	5.579
	s	$1.395 \times 10^2$	1.899	6.432
	$\bar{u}$	$3.371 \times 10^2$	1.434	5.999
	$\bar{d}$	$3.734 \times 10^2$	1.401	5.953
	g	$2.947 \times 10^3$	1.892	6.523
5.5	u	$7.961 \times 10^2$	1.293	5.580
	d	$9.478 \times 10^2$	1.254	5.539
	s	$1.228 \times 10^2$	2.174	6.418
	$\bar{u}$	$2.659 \times 10^2$	1.663	5.966
	$\bar{d}$	$2.908 \times 10^2$	1.624	5.924
	g	$2.449 \times 10^3$	2.192	6.519

or about 0.1 fm/c. We shall discuss the consequences of taking large formation times (see later).

Thus the azimuthal distribution of heavy quarks produced from interactions of thermalized partons is given by

$$\begin{aligned}
E_1 E_2 \frac{dN}{d^3p_1 d^3p_2} &= \frac{1}{16(2\pi)^8} \int d^4x \int d\phi_b dy_b \\
&\times \frac{p_{Tb0}}{[p_{T1} \cos(\phi_1 - \phi_b) + p_{T2} \cos(\phi_2 - \phi_b) - M_{T1} \cosh(y_1 - y_b) - M_{T2} \cosh(y_2 - y_b)]} \\
&\times \left[ \frac{1}{2} g_g^2 f_{\text{th}}^g(p_{Ta}) f_{\text{th}}^g(p_{Tb0}) \left| M_{gg \rightarrow Q\bar{Q}} \right|^2 \right. \\
&\left. + g_q^2 \sum_i \left\{ f_{\text{th}}^{q_i}(p_{Ta}) f_{\text{th}}^{\bar{q}_i}(p_{Tb0}) \left| M_{q\bar{q} \rightarrow Q\bar{Q}} \right|^2 + (q_i \leftrightarrow \bar{q}_i) \right\} \right] , \tag{20}
\end{aligned}$$

where (the boosted) thermal distribution of partons is approximated as

$$f_{\text{th}}(p_T, y, \eta) = \exp \left[ -\frac{p_T}{T} \cosh(y - \eta) \right] . \tag{21}$$

The above integration is done numerically, with the temperature varying according to Bjorken's cooling law, i.e.  $T^3 \tau = \text{constant}$ , till the temperature drops to about 160 MeV.

## 4. Results

### 4.1. Proton Proton Collisions

In the results to be reported in the following, we shall use the CTEQ5M structure function, though some results are also given for other structure functions. The mass of the charm quarks is kept fixed at  $m_c = 1.5$  GeV, while that for bottom quarks is  $m_b = 4.5$  GeV. The factorization and renormalization scales are taken as  $C\sqrt{m_Q^2 + p_T^2}$  with factor  $C = 2$  for charm quarks and 1 for bottom quarks. The NLO pQCD code (NLO-MNR) developed by Mangano et al. [24, 25] has been used for the initial production of heavy quarks.

*4.1.1. Production of heavy quarks, charmed mesons, and  $J/\psi$ :* The results for charm production along with recent results obtained at LHC for  $pp$  collisions are shown in Fig. 1. For the sake of exploration we have also included results for  $m_c = 1.2$  GeV and the structure function CTEQ5M. A very good description of the data Ref. [26], without any adjustment of parameters is seen (see also Refs. [17, 27]).

We have given the results of our calculations using several structure functions in Fig. 2 for the production of charm and bottom quarks at central rapidities in  $pp$  collisions at 2.76 TeV. We see that use of any of the more modern structure functions gives results which differ by just a few percent from each other.

One may also consider the production of D-mesons by writing schematically:

$$E \frac{d^3\sigma}{d^3p} = E_Q \frac{d^3\sigma(Q)}{d^3p_Q} \otimes D(Q \rightarrow H_Q) , \quad (22)$$

where the fragmentation of the heavy quark  $Q$  into the heavy-meson  $H_Q$  is described by the function  $D$ . We have assumed that the shape of  $D(z)$ , where  $z = p_D/p_c$ , is identical for all the  $D$ -mesons [28],

$$D_D^{(c)}(z) = \frac{n_D}{z[1 - 1/z - \epsilon_p/(1 - z)]^2} , \quad (23)$$

$\epsilon_p$  is the Peterson parameter and

$$\int_0^1 dz D(z) = 1 . \quad (24)$$

The production of a particular  $D$ -meson is then obtained by using the fraction for it, determined experimentally [29, 30].

A comparison of our results for  $D^0$  and  $D^+$  production with the preliminary data obtained by ALICE experiment [31] is shown in Fig. 3. We give results for  $\epsilon_p = 0.001$ , 0.06, and 0.12 to show the sensitivity of our calculations to this variation. Considering that no parameters have been adjusted, the results seem to be satisfactory. More detailed and accurate data will definitely put stringent constraints on all the inputs.

Note that the semi-leptonic decay of  $D$ -mesons has been extensively used to study the production of charm and bottom quarks, as well as the energy loss suffered by them. The electrons coming from charm decay, for example, are obtained by convoluting the

distribution of  $D$ -mesons (Eq. 22) with the electron decay spectrum [32] and accounting for the branching to a particular  $D$ -meson [29, 30]. In case the contributions of the  $B$  and the  $D$  mesons can not be distinguished, one should use the  $B$  and  $D$ -meson mixtures, with appropriate branchings,  $B \rightarrow e$ ,  $D \rightarrow e$  and  $B \rightarrow D \rightarrow e$ . The semileptonic decay of  $B$ -mesons becomes important at higher  $p_T$  in spite of their reduced production, though the contribution of the  $B \rightarrow D \rightarrow e$  channel drops rapidly with increase in  $p_T$  (see e.g., Ref. [33]).

The ALICE experiment has, however, obtained the single electrons from the process  $c \rightarrow D \rightarrow e$  [34]. The upgrades of STAR and PHENIX experiments at RHIC will also be able to measure this.

In Fig. 4, we compare our results for the electrons measured by the ALICE experiment with the decay of charm and a reasonable agreement is seen. In a future publication, we shall report on the consequences of introducing an intrinsic  $k_T$  for the partons and also using different parametrizations of the decay spectrum of the electrons.

The production of  $J/\psi$  in  $pp$  collisions is yet another important observable, which is closely related to the production of charm quarks. For example, using the colour evaporation model, one can write:

$$\frac{d\sigma_{J/\psi}}{dy} = F \int_{2m_c}^{2m_D} dM \frac{d\sigma_{c\bar{c}}}{dM dy} . \quad (25)$$

where  $M$  is the invariant mass of the pair,  $y$  is its rapidity,  $m_D$  is the mass of  $D$ -mesons, and  $F$  is the (constant) colour-evaporation factor which should be fixed by evaluation at some energy. There is one small detail which should be mentioned here; the LO pQCD calculations for heavy quark production produce  $c\bar{c}$  pairs with pair-momentum identically equal to zero (though the NLO processes do provide them with a net transverse momentum). This is corrected by imparting an intrinsic  $k_T$  to the partons (see e.g. [35]). *Only for these calculations* we impart an intrinsic  $k_T$  of 1.5 GeV/ $c$  to the partons.

We show our results for the transverse momentum and the rapidity distribution of  $J/\psi$  in Fig. 5 along with the experimental results for  $pp$  collision at 7 TeV obtained for prompt  $J/\psi$  by the LHCb experiment[36]. (Note that the ALICE collaboration has measured the inclusive  $J/\psi$  which includes the  $b$ -decays [37]. Even though this contribution is of the order of 10%, it is often accounted for by adding the  $b \rightarrow J/\psi$  contribution measured by the LHCb experiment.) We have explored the consequences of varying the intrinsic  $k_T$  on the  $p_T$  distribution of  $J/\psi$  and as expected the slope of the  $p_T$  distribution decreases with increase in  $k_T$ . A reasonable description of the distribution of the transverse momentum and the rapidity distribution is seen. An accurate description of the data will involve a more detailed exploration of the parameters. For example, the colour evaporation coefficient is kept fixed in these calculations, to magnify the effect of varying intrinsic  $k_T$ . Of-course the change of intrinsic  $k_T$  will not affect the rapidity distribution.

It will be interest to continue with this study for the prompt production of higher resonances of  $c\bar{c}$  as well as of  $b\bar{b}$ , when more accurate and detailed data become available.

*4.1.2. Correlations:* Having witnessed a good description of charm production as well as  $J/\psi$  production, we now move to the main topic of the present work. In the following we give our results for azimuthal, rapidity-difference, transverse momentum, and jet-radius correlation for charm and bottom quarks at 2.76 and 5.5 TeV for  $pp$  collisions. Deviations from these would signal medium modifications in case of nucleus-nucleus collisions.

Fig. 6 shows  $p_T$  and rapidity integrated  $\Delta\phi$  distribution for heavy quarks at  $\sqrt{s} = 2.76$  TeV, 5.5 TeV and 14.0 TeV for both leading order and next-to-leading order calculations. As expected the contribution rises with the energy available in the centre-of-mass system. It is felt that if our argument about heavy quarks not changing direction of their motion due to soft collisions with partons is valid, then drag (or energy loss) alone will not drastically alter this feature. It is needless to repeat that at LO all the heavy quarks will be produced back-to-back resulting in a peak at  $\Delta\phi = \pi$ . However, *if* the heavy quarks thermalize and flow with the medium, this picture may undergo change. We shall come back to this.

In Fig. 7 we show our results for the transverse momentum, rapidity, and invariant mass distribution of charm and bottom quark pairs produced in  $pp$  collisions at  $\sqrt{s}=2.76$  and 5.5 TeV. Recall that the pair momentum will be balanced by the momentum of the recoiling parton. Thus tagging on a high transverse momentum recoiling parton in the case of heavy ion collisions can give interesting details of how heavy quarks and (mostly) gluons behave in the medium produced in the collision. These results also contain a very interesting situation. Consider a heavy-quark produced in LO pQCD in a nucleus-nucleus collision. They will be produced back-to-back and are most likely to cover different part and length of the system, before they fragment (or coalesce with a light quark) to form a D-meson. Thus they would lose a differing amount of energy and acquire a net-transverse momentum which was initially identically zero. At least the co-linear heavy-quarks produced during splitting of a off-shell gluon would, on the other hand, cover similar distances under similar conditions in the plasma, and thus their net transverse momentum will remain largely unaltered. It would be interesting to study such cases in future more detailed experiments.

We show our results for rapidity correlation where,  $\Delta y = y_1 - y_2$ , of heavy quarks produced in such collisions in Fig. 8. We note that this correlation peaks at vanishing rapidity difference. We have also given the LO results for this along with a scaling of the LO results with a factor  $\sigma_{\text{NLO}}/\sigma_{\text{LO}}$  to demonstrate that the NLO results can not, in general, be approximated by a  $K$  factor multiplying the LO results, and the inadequacy of this shows up most strongly near  $\Delta y$  equal to zero. It is also likely that the rapidity difference, specially when the two rapidities have opposite signs may encode effects of longitudinal flow in case of nucleus-nucleus collisions.

Fig. 9 shows the results of our calculation for the jet-radius,  $R$ , correlation, where  $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ . It brings out the interesting differences between results for the leading order and next-to-leading calculations. Thus, while at leading order we do not have any contribution for  $R < \pi$ , there is a substantial contribution coming from

next-to-leading processes for  $0 < R < \pi$ .

#### 4.2. Lead Lead Collisions

Now we proceed to our results for collision of lead nuclei at 2.76 ATeV and 5.5 ATeV. In Fig. 10 we show our results for azimuthal distribution of heavy quarks produced from initial (prompt) collision of partons, having transverse momenta of 1–4 GeV and rapidities close to zero. The results for LO calculations, having a peak at  $\Delta\phi = \pi$  are given, to demonstrate the importance of using NLO results as a base line for these studies. We see a sharpening of the collinear and back-to-back correlations as the momenta of the quarks increases, while the correlation, with the exception of the peak at  $\Delta\phi = \pi$ , gets more flat, as NLO processes have a larger role, as the available energy increases. We also find less production of pairs of bottom quarks with smaller  $\Delta\phi$  at the same energy, compared to charm quarks, as expected.

We show our results for production of heavy quarks from multiple scattering of jets in Fig. 11. We have limited our calculations to contributions from quarks and gluons having  $p_T > 2$  GeV. Let us first consider our results for charm quarks. At both the energies, we see that while charm quarks having transverse momenta around 1.5 GeV, show a correlation which rises smoothly as we go from collinear to back-to-back correlations, the charm-quarks having larger transverse momenta give rise to a flat distribution for larger  $\Delta\phi$ . We also note that the contribution of multiple scattering of the jets, even though smaller at  $\Delta\phi \approx \pi$  compared to the contribution of initial production, is rather comparable at smaller angular separations. We note that as the initial and the final times  $\tau_i$  and  $\tau_f$  appear only as a multiplicative factor  $\ln(\tau_f/\tau_i)$ , the shape the correlation will remain unaffected by any change in their value.

The bottom quarks show a very interesting trend. For the lowest momentum considered, the bottom-quarks are seen to be produced with a flat azimuthal correlation, while as their momenta increase, the distribution becomes more and more collinear. The observation about comparable contributions of multiple scattering of jets and initial production at  $\Delta\phi < \pi$ , seen earlier for charm quarks, applies to them as well.

The results for the angular correlations of heavy quarks produced from the passage of jets through QGP are shown in Fig. 12. A very interesting and distinct picture emerges for these heavy quarks. We see that these productions are dominated by collinear contributions, confirming the nomenclature "jet-conversion" (see Ref. [12, 21]) for them. At small  $\Delta\phi$  their contribution is similar to that from initial production. The corresponding results for bottom quark-pairs show similar trends, but those are an order of magnitude smaller than the contribution of initial production.

And finally the results for the angular correlation of heavy quarks produced from scattering of thermalized partons is shown in Fig. 13. Firstly, these contributions are smaller by more an order of magnitude than the contributions discussed above. However, we still discuss their features as these are quite interesting. The azimuthal correlation of charm as well as bottom quark pairs is rather flat for low transverse momenta but

changes steadily to back-to-back at the transverse momentum increases. This, we feel, happens as heavy quarks having large transverse momenta can only come from collisions of partons having large  $\sqrt{s}$ . This would be possible for partons having almost equal and opposite momenta, thus leading to heavy quarks which will be predominantly back-to-back.

In order to get a feeling of the relative contributions of different mechanisms, we have shown the correlation of charm quarks for  $p_T \approx 2$  GeV/ $c$  and 4 GeV/ $c$  in Fig. 14. The first thing we note is that the shapes and relative contributions of the processes under consideration remain unchanged with the change in the momentum. Next we note that the multiple scattering among the high energy gluons and quarks, termed jet-jet interaction, gives rise to a rather flat azimuthal correlation between the charm quarks, which is comparable to the results for prompt production for  $\Delta\phi \neq \pi$ . The next large contribution is due to the jet-thermal contribution, which is rather flat for  $\Delta\phi \in [0 : 2]$  and then falls rapidly. Over this region it is again comparable to the prompt and the jet-thermal contributions. The thermal contributions are peaked toward  $\Delta\phi = \pi$  and are rather small.

Recall that we have used a formation time of the plasma as 0.1 fm/ $c$ , inspired by the parton saturation model. A larger value for  $\tau_i$  will leave the jet-jet contribution essentially unchanged, as we discussed earlier. However the jet-thermal and thermal contributions are expected to drop if the initial time is increased. Thus recalling our results from Ref. [10], we estimate that raising the  $\tau_i$  to 0.5 fm/ $c$  the jet-thermal contribution may decrease by a factor of 2, while the thermal contribution will come down by a factor of about 4.

### 4.3. Effect of Flow

We have suggested earlier that the effect of drag or energy loss of heavy quarks alone may not be enough to change their direction of motion, and thus the  $p_T$ -integrated azimuthal correlations discussed in this work may not be affected by the energy loss. It may change for a given  $p_T$  due to migration of quarks to the regions of lower  $p_T$  and the  $p_T$  dependence of the heavy quark production. The flow of the medium can, however, affect the angular correlation considerably, if it is large and if the heavy quarks are thermalized. In order to estimate the effect of the flow on the correlation of the heavy quarks, we use a toy model used earlier by Cuautle and Paic [38], and more recently in Ref. [39], for studying correlations.

In order to do this, we proceed as follows. We first give a random orientation to the quark-pairs from the NLO pQCD calculations (the NLO MNR code, e.g., at LO gives pairs with  $p_{x_1} = p_{x_2} = 0$ ). Then we place them at  $(x, y)$ , randomly chosen according to the probability:

$$P = \frac{\int \int dx dy T_A(x, y, b=0) T_B(x, y, b=0)}{T_{AB}(b=0)}, \quad (26)$$

where  $T_i$  is the transverse density profile of the nucleus  $i$  assumed to have a uniform

density of radius  $R$ , and  $T_{AB}(b = 0)$  is the nuclear thickness for impact parameter,  $b = 0$ . Assuming a flow, directed away from the centre, we add the flow momentum  $\mathbf{p}_{Tf} = p_{Tf} (\mathbf{r}/r)$  to the momentum of the heavy quark  $\mathbf{p}_T$ .

We use the blast-model [40] to write  $p_{Tf}$  as

$$p_{Tf} = \gamma\beta_r m_Q, \quad (27)$$

where

$$\beta_r = \beta_s \times \left( \frac{r}{R_T} \right)^2. \quad (28)$$

and  $r = \sqrt{x^2 + y^2}$ . We give results for  $\beta_s = 0, 0.3$ , and  $0.6$ . We show our results Fig. 15 for two ranges of  $p_T$  of the charm quarks,  $p_T < 4$  GeV and  $p_T > 4$  GeV. We see that even though the azimuthal correlation is more strongly affected for charm quarks having lower transverse momenta for reasonable values of the flow, the basic nature of the correlation function remains unchanged. It is likely that if the charm quarks are not completely thermalized, the effective flow velocity for them could be smaller, and then the above observation becomes even more relevant. Note that large values of  $\beta_s$  are normally reached only in the hadronic phase.

## 5. Summary

We have calculated azimuthal, rapidity difference, and transverse momentum correlations of heavy quark pairs produced in  $pp$  collisions at several energies relevant for experiments being done at the Large Hadron Collider, using NLO pQCD. Wherever possible, we have discussed how these could change due to final state effects in nucleus-nucleus collisions. These results will act as a base-line for similar studies in the case of  $Pb + Pb$  collisions at the corresponding centre of mass energies/nucleon, to determine medium modifications. We have noted that this picture is enriched (or complicated) by multiple collisions among the partons having high energy, which can give very different correlations of a magnitude comparable to that of initial productions considered above. We have argued, but it remains to be verified, that these correlations may not be drastically altered due to the energy loss suffered by heavy quarks, as they may not change the direction of their motion substantially, due to soft scatterings. These may however, be affected by a strong flow of the medium, if the heavy quarks are thermalized.

In a forth-coming publication we shall address the issue of consequences of energy loss on these correlations.

## Acknowledgments

One of us (MY) acknowledges financial support of the Department of Atomic Energy, Government of India during the course of these studies. (UJ) acknowledges hospitality at VECC where part of this work was done.



## References

- [1] C. Shen, S. A. Bass, T. Hirano, P. Huovinen, Z. Qiu, H. Song and U. W. Heinz, Phys. Rev. Lett. **106**, 042301 (2011) arXiv:1106.6350 [nucl-th], H. Song, S. A. Bass, U. Heinz Phys. Rev. C **83**, 054912 (2011), B. Schenke, S. Jeon, C. Gale Phys. Rev. Lett. **106**, 042301 (2011).
- [2] Y. L. Dokshitzer, V. A. Khoze, S. I. Troian, J. Phys. G **17**, 1602 (1991); Yu. L. Dokshitzer, D. E. Kharzeev, Phys. Lett. B **519**, 199 (2001).
- [3] R. Thomas, B. Kampfer, G. Soff, Acta Phys. Hung. A **22**, 83 (2005); N. Armesto, C. A. Salgado, U. A. Wiedemann, Phys. Rev. D **69**, 114003 (2004).
- [4] W. C. Xiang, H. Ding, D. Zhou, Chin. Phys. Lett. **22**, 72 (2005).
- [5] H. van Hees and R. Rapp, Phys. Rev. C **71**, 034907 (2005) [arXiv:nucl-th/0412015], P. B. Gossiaux, V. Guiho and J. Aichelin, J. Phys. G **32**, S359 (2006).
- [6] B. Svetitsky, Phys. Rev. D **37**, 2484 (1988), M. G. Mustafa, D. Pal and D. K. Srivastava, Phys. Rev. C **57**, 889 (1998) [Erratum-ibid. C **57**, 3499 (1998)], Santosh K. Das, Jan-e Alam, P. Mohanty, Phys. Rev. C **82**, 014908 (2010).
- [7] R. Rapp, H. van Hees, arXiv:0803.0901v2 [hep-ph], H. van Hees, M. Mannarelli, V. Greco, R. Rapp Phys. Rev. Lett. **100**, 192301 (2008), R. Rapp, H. van Hees, J. Phys. G **G32**, S351 (2006).
- [8] N. Xu, X. Zhu, P. Zhuang, Phys. Rev. Lett. **100**, 152301 (2008), N. Xu, X. Zhu, P. Zhuang, J. Phys. G **36**, 064025 (2009).
- [9] Z. W. Lin and M. Gyulassy, Phys. Rev. C **51**, 2177 (1995) [Erratum-ibid. C **52**, 440 (1995)].
- [10] Md. Younus, D. K. Srivastava, J. Phys. G Nucl. Part. Phys. **37**, 115006 (2010).
- [11] P. Levai, B. Müller, X. N. Wang, Phys. Rev. C **51**, 6 (1995).
- [12] W. Liu, R. J. Fries, Phys. Rev. C **77**, 054902 (2008), W. Liu, R. J. Fries, Phys. Rev. C **78**, 037902 (2008).
- [13] A. Shor, Phys. Lett. B **215**, 375 (1988).
- [14] E. Batten, M. H. Thoma, Phys. Rev. D **44**, R2625 (1991), M. G. Mustafa, D. Pal, D. K. Srivastava and M. Thoma, Phys. Lett. B **428**, 234 (1998), M. Djordjevic and M. Gyulassy Nucl. Phys. A **733**, 265 (2004), S. Wicks, W. Harowitz, M. Djordjevic, M. Gyulassy, Nucl. Phys. A **784**, 426 (2007), W. -C. Xiang, H. T. Ding, D. C. Zhou, D. Rohrick Eur. Phys. J **A25**, 75 (2005), N. Armesto, C. A. Salgado, U. A. Wiedemann, Phys. Rev. D **69**, 114003 (2004), M. G. Mustafa, Phys. Rev. C **72**, 014905 (2005), (erratum) Phys. Rev. C **74**, 019902 (2006), S. Peigne, A. Peshier, Phys. Rev. D **77**, 114017 (2008).
- [15] T. Renk, Phys. Rev. C **74**, 034906 (2006).
- [16] X. -N. Wang, Phys. Lett. B **B595**, 165 (2004), A. Mischke, [nucl-ex/1107.5138v1].
- [17] E. Eichten, I. Hinchliffe, K. Lane, C. Quigg, Rev. Mod. Phys. **56**, 4 (1984) U. Jamil, D. K. Srivastava, J. Phys. G Nucl. Part. Phys. **37**, 085106 (2010).
- [18] S. Vogel, P. B. Gossiaux, K. Werner, J. Aichelin, Phys. Rev. Lett. **107**, 032302 (2011), F. -M. Liu, K. Werner, Phys. Rev. Lett. **106**, 242301 (2011).
- [19] B. L. Combridge Nucl. Phys. B **151**, 429 (1979).
- [20] K. Aamodt et al(ALICE Collaboration), Phys. Rev. Lett. **105**, 252301 (2010).
- [21] Rainer J. Fries, B. Müller, D. K. Srivastava, Phys. Rev. Lett., **90**, 132301 (2003).
- [22] J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).
- [23] K. J. Eskola, H. Honkanen, H. Niemi, P. V. Ruuskanen, S. S. Rasanen, Phys. Rev. C **C72**, 044904 (2005). [hep-ph/0506049].
- [24] M. L. Mangano, P. Nason, G. Ridolfi, Nucl. Phys. B **373**, 295 (1992).
- [25] S. Frixione, M. L. Mangano, P. Nason, G. Ridolfi, Adv. Ser. Direct. High Energy Phys. **15**, 609-706 (1998). [arXiv:hep-ph/9702287 [hep-ph]].
- [26] A. Dainese (ALICE Collaboration), Quark Matter 2011, Annecy, France.
- [27] R. Vogt, Acta Phys. Polon. Supp. **1**, 695 (2008), N. Carrer, A. Dainese [hep-ph/0311225].
- [28] C. Peterson, D. Schlatter, I. Schmitt, P. M. Zerwas, Phys. Rev. D **D27**, 105 (1983).

- [29] A. Aktas *et al.* [ H1 Collaboration ], Eur. Phys. J. **C38**, 447-459 (2005). [hep-ex/0408149].
- [30] ZEUS Collaboration, JHEP **07**, 074 (2007).
- [31] A. Dainese, [ ALICE Collaboration], Talk given at QM 2011.
- [32] G. Altarelli, N. Cabibbo, G. Corbo, L. Maiani, G. Martinelli, Nucl. Phys. **B 208**, 365 (1982).
- [33] M. Cacciari, P. Nason, R. Vogt, Phys. Rev. Lett. **95**, 122001 (2005).
- [34] A. Mischke, [ ALICE Collaboration], arXiv:1106.1011.
- [35] G. T. Bodwin, E. Braaten, J. Lee, Phys. Rev. D **72**, 014004 (2005).
- [36] R. Aaij et al., [ LHCb Collaboration ], Eur. Phys. J. **C 71**, 1645 (2011).
- [37] K. Aamodt *et al.* [ALICE Collaboration ], Phys. Lett. **B704**, 442-455 (2011). [arXiv:1105.0380 [hep-ex]].
- [38] E. Cuautle, G. Paic, AIP Conf. Proc. **857**, 175-178 (2006). [hep-ph/0604246].
- [39] G. Tsileadakis, H. Appelshäuser, K. Schweda, J. Stachel, Nucl. Phys. A **858**, 86 (2011),  
G. Tsileadakis, K. Schweda, Proc. of the ISMD08 Conf., DESY-PROC -2009-001, 2009, p. 214,  
G. Tsileadakis, Proc. of the 417<sup>th</sup> WE-Heraeus-Seminar, 2008, (Bad Honnef).
- [40] E. Schnedermann, J. Sollfrank, U. W. Heinz, Phys. Rev. **C48**, 2462-2475 (1993).